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FATIGUE LIFE OF STRANDED HOOK-UP WIRE

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Increasing use of electronic equipment in both ground vehicles and aircraft has caused many new problems in the hook-up wire field. Especially is this true in aircraft equipment, where size and weight reduction are of increasing importance, the resultant trend toward miniaturization requires physically smaller wires and cables wherever electrical considerations will permit. Here many circuits employ practically infinitesimal currents so that the factor determining conductor size usually becomes simply mechanical strength. Extremely difficult envinronmental conditions are also frequently encountered, and equipments must be operable over wide temperature ranges and under conditions of severe mechanical abuse.

Since this mechanical abuse often takes the form of fatigue induced by vibration, completed equipments must be subjected to vibration tests before acceptance by the Armed Services. Consequently, it has been proposed that individual components should be subjected to similar tests before they are accepted for use in completed equipments. Such tests have been considered from time to time for wire and cable specifications. Unfortunately since the resonance frequencies and amplitudes of vibration are dependent upon terminations and fastening techniques used, a vibration test on the wire itself will mean very little unless the precise manner in which the wire or cable is to be installed in service is used during the vibration test.

Hook-up wires are exposed to three types of fatigue: (1) vibration; (2) sharp bending during installation, modification, and servicing; and (3) intentional flexing in service. As stated, vibration is very difficult to simulate in the laboratory. The second type, sharp installation-bending, is also difficult to reproduce because each installation and each installing activity have different wiring problems and technicians servicing equipment in the field subject the wires to varying degrees of abuse. When, as in the third case, a cable is required for flexing service, the application is usually known in advance so that laboratory procedures may be established which will accurately simulate the service use. In order to make laboratory studies of vibration and installation difficulties some sort of bending techniques must be resorted to in an attempt to evaluate the relative merits of wires and to compare constructions, materials, and installation techniques.

Since Surprenant Mfg. Co. specializes in wire and cable for this type of service, it has been necessary to resolve innumerable problems of this sort, and this paper presents experimental data obtained for the purpose of solving such problems. It should be borne in mind that these data were taken at several different times for individual problems so that test conditions vary widely from one test to another. The variables which enter into the picture are so numerous that it is not possible in some cases to correlate the data among the different tests. But because the results as presented here are averages of several different readings which were very consistent among themselves, the data does give good comparisons based on individual tests. The data appear to be quite reliable horizontally provided the test conditions are kept in mind. Some of the variables which can enter into the picture have already been mentioned, i.e., whether the bending is due to vibration, intentional sharp bending, or loose flexing. Other factors include: the wire size and stranding, conductor material, the type of insulation, and the method of termination. The last mentioned includes a number of variables depending on whether the wires are soldered or crimped, the type of lug used, whether the insulation is supported at the lug or not and how the wire is fastened to the equipment itself.

The equipment used for making the tests are shown in figures 1 through 5. In figures 1, 3, and 4 the motion consists of a longitudinal oscillation of the bar in the foreground of the picture of one inch at approximately twelve complete cycles per second. A counter on the same shaft as the crank records the number of complete cycles during the test. In the tests illustrated in these three figures the remainder of the apparatus to the right is either unused or used only as a vise to hold the test specimen.

In figure 2 the oscillating bar is not used. The pinion shaft to which the wire specimen is attached oscillates at a rate of approximately 1½ cycles per second, producing a sharp bend in the wire at the point of attachment. The wire specimen is placed under the desired tension by the spring in the extreme foreground. The crank throw can be adjusted to obtain any desired angular oscillation of the pinion shaft.

In figure 5 a 1725 rpm motor drives a 100 to 1 gear reduction by means of pulleys and belt. The gear reduction in turn drives a crank, connecting rod, rack, and pinion to oscillate the long arm in angular fashion through any desired angle between plus and minus 45° and plus and minus 90° by adjusting the crank throw. The number of complete oscillations are recorded on the counter at the extreme right.

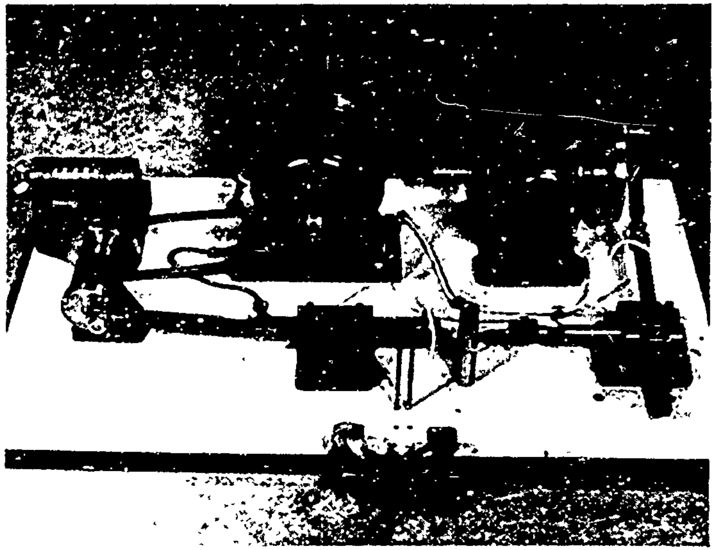

FIGURE 1

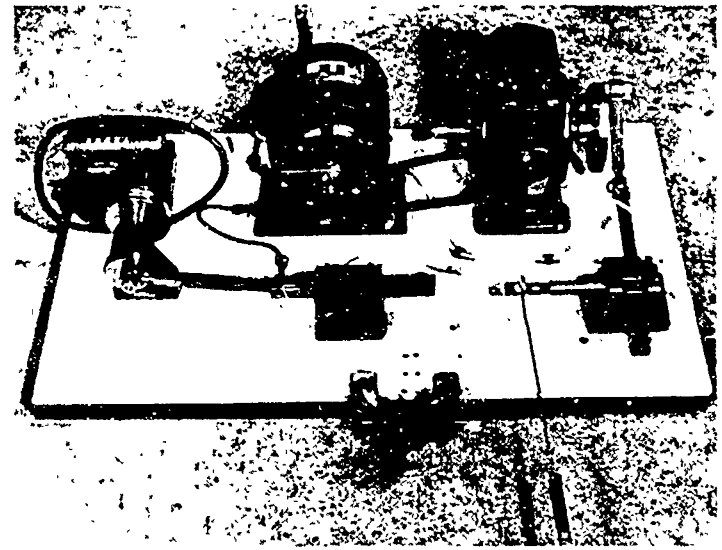

FIGURE 2

FIGURE 3

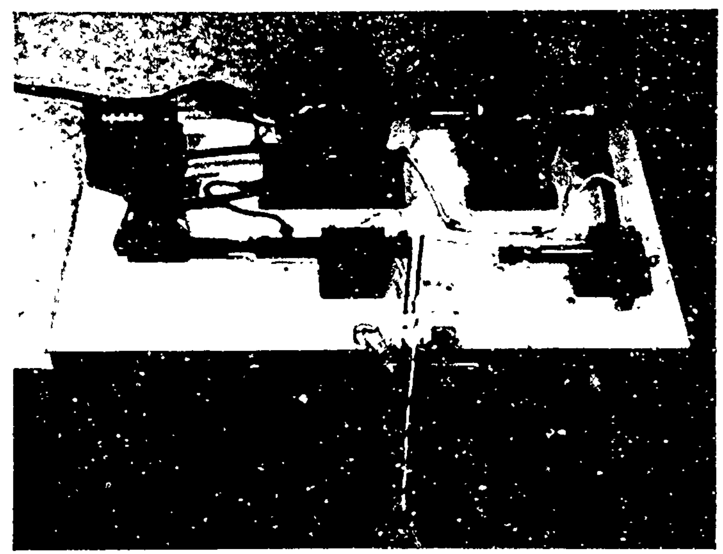

FIGURE 4

FATIGUE TESTS MADE ON OSCILLATING BAR MACHINE

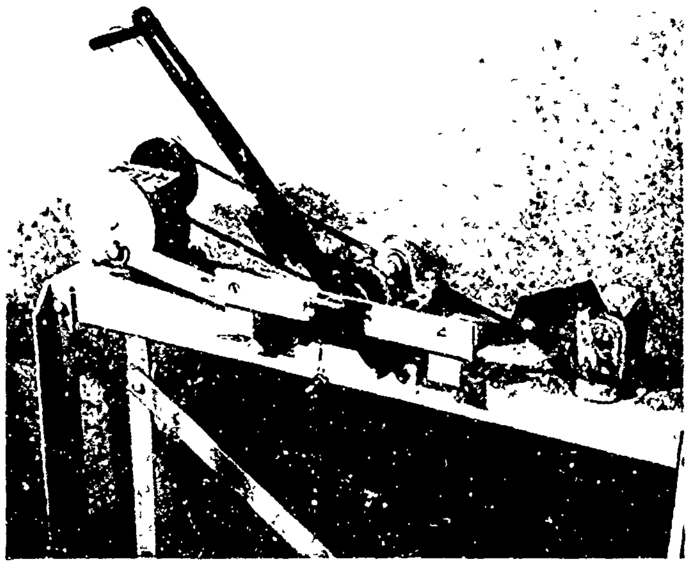

FIGURE 5
ROTATING BAR MACHINE

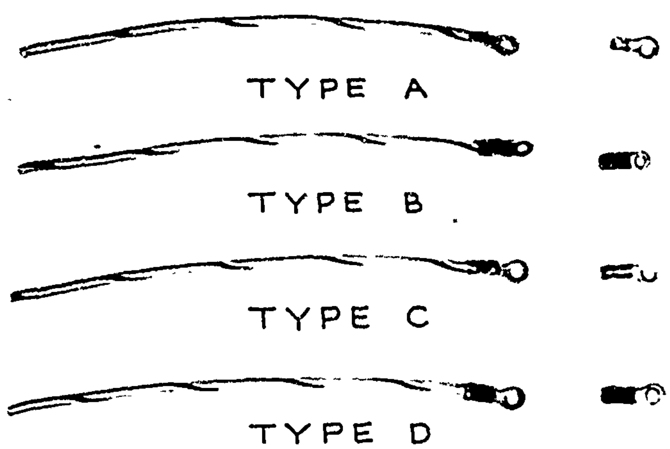

FIGURE 6
TERMINAL TYPES

The apparatus shown in figures 1 and 5 are used to simulate applications where bending is deliberate and controllable in practice. The severity of the bend can be varied in figure 1 by the size of the post used. In figure 5 the bend may be varied by the size of the two mandrels between which the wire passes and by the amount of weight hung on the conductors.

The arrangement as shown in figure 2 is used to produce sharp bending such as would be encountered in moving harnesses about during installation or servicing. Several tests reported later in the paper also accomplished this type of bending by hand over the edges of a vise. In an attempt to simulate vibratory conditions, the apparatus arranged as shown in figures 3 and 4 is used. Vibration of wires or wire harnesses attached to terminals usually results in a sharp bend of a small angle. In figure 3 such a bend is produced at the point of clamping to the oscillating bar. For comparison purposes and to produce the same bend from sample to sample a known length of wire is clamped at the same point each time in the oscillating bar and the stationary piece at the right of the picture. In figure 4 the bend is produced by clamping the wire at right angles to the oscillating bar and passing it between two vertical pins located a fixed distance away from the bar as shown. The test specimen passes over a sheave and has a known weight attached. For most of the tests, the pins were located an inch and a half from the leading edge of the oscillating bar. This test gave results which were slightly more reproducible than the tests shown in figure 3, so that the majority of the results reported in this paper, where an attempt was made to represent vibrating conditions, were obtained by the test method indicated in figure 4.

In all of the testing, the conductor under test forms a part of the circuit operating the drive motor so that failure of the wire stops the equipment leaving the number of cycles recorded on the counter. For the sharp bending as conducted in figure 2 and for those tests done by hand the cycles were counted since very few cycles were required.

The use of aluminum wire has been attractive to aircraft manufacturers since for a given current carrying capacity a saving in conductor weight of about one-half may be achieved. Aluminum has been used in large power cables in several airplanes and consideration has been given to the use of this material for smaller size interconnecting wire. The weight saving here could be considerable when one consider that some types of aircraft have as much as 250 pounds of #20 wire alone. With this in mind, studies were made to evaluate the possibility of using aluminum wire in place of copper. Of course a primary requirement for aircraft wire is its fatigue life under conditions of vibration. Since aluminum is extremely difficult to solder properly the problem of terminations was looked into at the same time.

Four types of crimp terminals were used in comparing aluminum with copper as shown in figure 6. Type A has a short metal sleeve in which the stripped conductor is inserted and a pressure joint is formed by crimping the terminal with a special tool. The type B terminal is similar to type A except that a semi-flexible insulating sleeve extends back over the insulation so as to help relieve the strain appearing at the point where the insulation is stripped from the conductor. The type C terminal has a longer metal sleeve so that the insulation may be inserted into it a short distance and the joint made as before. The type D lug is built exactly like type C except that the metal sleeve has insulation over it. As expected the data which follows shows that there is no significant difference between types C and D connectors.

In all of the tests conducted, tinned or silver plated soft drawn copper wire was used as a control for comparison purposes and serves as a basis for drawing conclusions between various tests.

For the aluminum comparisons, a #20 AWG wire made up of seven strands of #28 insulated with a vinyl insulation (Surprenant Mfg. Co., B 2 formulation.) with an outside diameter of .075" was used. In addition to the soft tinned copper, electrical conductor grade aluminum (ECH-19) and an aluminum alloy (56-S) were tested. The 56-S grade of aluminum is a high tensile strength aluminum alloy used for metallic braids and armors in the cable industry. This test was conducted using the technique shown in figure 4, since it was desired to simulate the effects of vibration. The two pins were located one and one half inches from the leading edge of the oscillating bar. The results are summarized in table I.

TABLE I

(All numerical values are test cycles.)

Connector Type A	Copper	56-S	ECH-19
Uninsulated wire	3710	7387	260
Insulation clear of connector	1614	4098	177
Connector Type B			
Uninsulated wire	8945	20643	1877
Insulation clear of connector	11004	14129	1274
Insulation inside connector	10354	20203	2093

Connector Type C			
Uninsulated wire	5583	8770	525
Insulation clear of connector	3724	5496	479
Insulation inside connector	1902	4074	403
Connector Type D			
Uninsulated wire	5687	11552	632
Insulation clear of connector	4075	3571	686
Insulation inside connector	2405	4844	402

An examination of these data brings out several interesting ideas. The uninsulated wire stood up much better than the w[illegible] the insulation stripped back beyond the connector sleeve. This was expected since the insulation serves to stiffen the wire and produce a hinging action between the insulation and connector which gives a more severe bend than that obtained in the uninsulated wire.

There is no significant difference in the behavior of connectors C and D.

Connector type A consistently made the poorest showing. This terminal had no sleeve for insulation support, hence, all connections were made with the wire insulation clear of the connector.

Connector type B is far superior to any of the other types since the insulating bushing is semi-flexible and acts to cushion the bends. This effect is especially noticeable when the insulation extends inside the sleeve.

Comparison of materials definitely shows that the electrical conductor grade aluminum would not be suitable in hook-up wire sizes for an application where vibration is a problem. The aluminum alloy appears in every case to be considerably better than the soft copper, however, the conductivity is only 29% that of copper so that for the same current carrying capacity, no weight saving is had in the conductor itself. Therefore, the conductor would be larger and bulkier and would require more insulation so that the finished wire would be heavier than the equivalent copper conductor.

Further work was done with the same connectors with copper wire only, to try to determine the effect of soldering with the various types of lugs. A soldered connection in the type A lug is very similar to a connection soldered to a pin, tube socket, potentiometer, etc.

Exact comparison cannot be made with the data shown in table I since in this test seven strands of #26 (#18 AWG) tinned copper were used with a vinyl insulation and vinyl insulation with nylon jacket, as well as uninsulated conductor.

Table II once more clearly shows the superiority of the type B connector with the type A connector again giving the poorest results. Type C and D connectors show very little difference in their behavior and lie between A and B in their performance.

TABLE II

(All numerical values are test cycles.)

	Connector Type			
	A	B	C	D
A. Crimped Connection				
1. Uninsulated	1728	2817	2611	2258
2. Vinyl Insulation Only				
Insulation clear of connector	630	2360	1281	702
Insulation inside connector		2416	1206	1304
3. Vinyl Insulation With Nylon Jacket				
Insulation clear of connector	557	2053	950	467
Insulation inside connector		2462	1038	896
B. Soldered Connection				
1. Uninsulated	1655	1911	1785	2[illegible]67
2. Vinyl Insulation Only				
Insulation clear of connector	594	723	300	588
Insulation inside connector		3216	2050	3007
3. Vinyl Insulation With Nylon Jacket				
Insulation clear of connector	377	1501	536	433
Insulation inside connector		3716	1313	1664

An unexpected result was obtained in every case where the insulation was supported inside the sleeve. In this instance the soldered connections gave noticeably better fatigue life than the crimped fastening. The reason for this is that the solder stiffens the conductor to such an extent that the bending occurred back in the in..lated part of the conductor away from the connector itself. When the insulation was not supported however, the exact reverse was true because the bending still took place where the conductor was exposed and the solder had run back, fusing the strands together and making in effect a solid wire.

On the average it appears that the nylon jacket has very little effect on the performance of the wire. Again in this series of tests the uninsulated wire stood up better than the insulated wire. The variation between individual readings was somewhat greater for the soldered connections than for the crimped connections.

A third series of tests were run on bare copper, 56 S grade aluminum, and cadmium bronze. These tests were conducted for specific purposes so that the wire sizes are not the same for the aluminum and the cadmium bronze, however, in both cases a copper conductor identical to the corresponding aluminum and cadmium bronze were tested. In order to evaluate the relative merits of cadmium bronze versus the aluminum alloy a ratio of aluminum to copper and cadmium bronze to copper was calculated for each case.

TABLE III

	Copper	Aluminum 56-S	Ratio
#28 Solid	6118	8192	1.32
#20 (7/28)	10239	17552	1.71
	Copper	Cadmium Bronze	
#35 Solid	11009	35007	3.19
#27 (7/35)	14587	45513	3.12

Table III shows the results of a deliberate flexing tested as shown in figure 1. For the larger wires, that is, #28 and #20 a ½" post was used. When the #35 and #27 wires were tested, it was found that the ½" post would give well over 100,000 cycles before failure so that the post diameter was reduced to ¼" to give a sharper bend to the wire to obtain a reasonable test time. Table III shows comparisons of the data taken in this fashion. Again the high tensile aluminum alloy shows up somewhat better than the annealed copper and the cadmium bronze is far better for this type of flex.

TABLE IV

	Copper	Aluminum 56-S	Ratio
#28 Solid	6.5	2.6	.40
#20 (7/28)	14.3	6.6	.46
	Copper	Cadmium Bronze	
#35 Solid	8.0	3.6	.45
#27 (7/35)	21.6	8.1	.38

Several tests were made giving conductors sharp bends such as would be experienced in moving harnesses about during installation or servicing. Data shown in table IV represents a total bend of 180° obtained by application of hand pressure at the bending point. The wire was held in a small vise and bent 90° to the right and 90° to the left. These data very clearly show the advantage of copper over the higher tensile strength materials for this type of bend.

TABLE V

	Copper	Aluminum 56-S	Ratio
#28 Solid	7	3.4	.49
#20 (7/28)	58	18.8	3.2
	Copper	Cadmium Bronze	
#35 Solid	4	2.6	.65
#27 (7/35)	17	13.4	.79

The apparatus shown in figure 2 was used to obtain the data in table V. The wire strand was clamped as shown to the rotating member and placed under about two ounces of spring tension. The shaft was then rotated about 90° in each direction. The low spring tension provided a less severe bend than the manual bending. In every case and paricularly in the case of the #20 wire the stiffness was great enough to produce a longer sweeping bend requiring more bends to fail the wire. This gives the stiff #20 aluminum wire a noticeable advantage.

In order to simulate a sharp bend through a small angle the apparatus in figure 3 was used. This test gave a small angle but a rather sharp bend directly at the point of clamping and all failures occurred at this point. Reference to table VI will show the results here. These indicate a degree of bending lying between the test results shown in table III and table IV. The #35 solid appears to give the cadmium bronze an abnormally high advantage and should be viewed with suspicion.

TABLE VI

	Copper	Aluminum 56-S	Ratio
#28 Solid	571	477	.84
#20 (7/28)	1042	828	.80
	Copper	Cadmium Bronze	
#35 Solid	3116	17722	5.7
#27 (7/35)	3595	9311	2.5

TABLE VII

	Copper	Cadmium Bronze	Beryllium Copper	Copperweld
Insulation less than 1/64″ from terminal	27	263	1294	3040
Insulation 1/4″ from terminal	104	952	3671	8745

A few tests were conducted to obtain some quick comparisons with other materials. The method used here is that shown in figure 4 using terminal type A soldered with a thirteen ounce weight hung on the conductor. All conductors in this test were silver plated. The wire used consisted of 19 strands of #36 conductor with a mono-chlorotrifluoroethylene insulation having an outside diameter of .046″. These tests were done with the insulation brought up to with 1/64″ of the terminal sleeve and repeated with the insulation about a 1/4″ away from the sleeve as shown in table VII. It is apparent from these figures that longer life is obtained when the insulation is stripped back somewhat from the connector if a soldered joint is used. This result is expected since this type of insulation is quite stiff and the solder runs back slightly under the insulation when the insulation is very close resulting in a solid wire where the bending takes place. The solder did not run back 1/4″ so that in the second instances the flexing occurred in a part of the conductor where the strands were not bonded together. The data indicates for this type of bending that copperweld is far superior to other materials with beryllium copper much better than cadmium bronze or soft annealed copper. Further work remains to be done here with other type of insulation. Because of the inherent stiffness of the material used for these tests it may well be that the extra stiff conductors give a misleading comparison.

TABLE VIII

	Copper	Cadmium Bronze	Beryllium Copper	Copperweld
Sharp Angle Bend	8	3	13	30

Since these tests show copperweld and beryllium copper in such a favorable light, further tests were conducted on the same four metals by bending them through a sharp angle of plus and minus 90° by hand. The data as shown in table VIII again shows beryllium copper and copperweld superior to the other two metals. Comparison of the copper and cadmium bronze figures with those shown in table IV shows the reproducibility of this type of test rather clearly. The fact that an average number of flexes is almost the same for the two cases is not significant because one was conducted with #35 solid wire and the other conducted with 19 strands of #36; but the fact that the ratio beween the copper and cadmium bronze is almost the same tends to lend confidence in the experimental work since the data were taken at two widely separate intervals by different observers.

Work is presently being carried on to determine the optimum number of strands and lay length for hook up wires in regard to bending life. The equipment being used for this series of tests is shown in figure 5, one cycle consisting of a 90° bend in each direction. The work which has been done used #18 AWG wire with the following strandings. 7 of #26, 19 of #30, 65 of #36, and 105 of #38 tinned copper with a vinyl insulation (Surprenant Mfg. Co., formulation B-2) with an outside diameter of approximately .078". The results are shown in table IX.

TABLE IX

7 strands of #26	351
19 strands of #30	874
65 strands of #36	2892
105 strands of #38	2908

There appears to be a definite advantage to a large number of fine strands although the improvement levels off at some point. Enough work has not yet been done to determine where this point occurs for various sizes. The 105 strands of #38 were tested with several thicknesses of insulation with no significant difference in number of bends before failure.

In this paper all values reported are averages of at least six different readings. The individual readings did not vary widely although in some cases where soldering was involved the spread was increased slightly. The data, of course, is reliable only to the extent that the test conditions represent the service in the field.

The connectors studied were only used to determine principles involved. Since there are hundreds of terminals available from several manufacturers an exhaustive study of this problem was not attempted. Undoubtedly there are connectors available which will give better results than the relatively simple types used in these tests.

A great deal of work still remains to be done. In view of the data shown in table VII further study of beryllium copper and copperweld is warranted. Samples are now being prepared to continue the work started on the #18 wire by finding the optimum lay length and extending the studies to other conductor sizes for this type of flexing service. Some of the results of this paper have been found useful in practice but a great deal more information from the field is necessary to determine how well these tests simulate the actual service conditions to which the wire is subjected. This type of information is slowly being accumulated with the hope that the most suitable materials may be applied in the optimum construction for any particular application.

PROPERTIES OF MATERIALS CONSIDERED

	Soft Annealed Copper	Aluminum ECH-19	Aluminum 56-S	Cadmium Bronze	Beryllium Copper	Copperweld 40% conductivity grade
Density at 20°C gm/cc	8.96	2.71	2.64	——	8.85	8.15
Specific heat at 20°C cal/gm	.092	.230	.23	- - -	——	——
Volume conductivity referred to standard copper	1.03	.62	.27	.83	.60 - .62	.40
Average tensile strength—p.s.i.	33,000	26,000	60,000	105,000	125,000	115,000
Average elongation % in 10"	20	1	4	2	1	1